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Published in:
Optics Express

Link to article, DOI:
[10.1364/OE.18.024969](https://doi.org/10.1364/OE.18.024969)

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Rodes Lopez, R., Jensen, J. B., Zibar, D., Roenneberg, C. N., Roskopf, J., Ortsiefer, M., & Tafur Monroy, I. (2010). All-VCSEL based digital coherent detection link for multi Gbit/s WDM passive optical networks. *Optics Express*, 18(24), 24969-24974. <https://doi.org/10.1364/OE.18.024969>

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All-VCSEL based digital coherent detection link for multi Gbit/s WDM passive optical networks

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Abstract: We report on experimental demonstration of a digital coherent detection link fully based on vertical cavity surface emitting lasers (VCSELs) for the transmitter as well as for the local oscillator light source at the receiver side. We demonstrate operation at 5 Gbps at a 1550 nm wavelength with record receiver sensitivity of -36 dBm after transmission over 40 km standard single mode fiber. Digital signal processing compensates for frequency offset between the transmitter and the local oscillator VCSELs, and for chromatic dispersion. This system allows for uncooled VCSEL operation and fully passive fiber transmission with no use of optical amplification or optical dispersion compensation. The proposed system demonstrates the potential of multi-gigabit coherent passive optical networks with extended reach and increased capacity. Moreover, this is, to the best of our knowledge, the first demonstration of coherent optical transmission systems using a low-cost VCSEL as the local oscillator as well as for the transmitter.

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OCIS codes: (000.0000) General; (000.2700) General science.

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1. Introduction

Next generation fiber-to-the-customer networks (FTTC) need to comply with a set of technical requirements, including support of a large number of end customers with emerging services, such as HDTV, demanding a high bandwidth surpassing 1 Gbit/s [1]. This requirement can be achieved e.g. by increasing the bit-rate of current time-domain

multiplexing (TDM) access systems and introducing a higher splitting ratio reaching the order of 1000 [2]. Another alternative is to employ wavelength division multiplexing (WDM), or to combine WDM and TDM approaches [3]. Conventional WDM approaches based on passive filtering by arrayed waveguide gratings (AWGs) are challenging for ultra-dense wavelength spacing, and the introduction of such architecture is therefore not straightforward in future access networks employing splitting ratios approaching 1000. Likewise, direct increase of passive splitting ratio in current TDM PONs is problematic due to the increased splitting loss. Other important challenges are the need for graceful migration and flexibility in order to support scalability as the network grows; a feature not straightforward compatible with a fixed AWG-based WDM architecture. These challenges motivate interest in optical fiber access solutions based on coherent detection due to its advantages of support of closely spectrally spaced channels with electrical narrow bandwidth selection [4], increased receiver sensitivity [5] and support for advanced modulation formats [6]. Moreover, with recent advancements in digital signal processing (DSP) [7] for optical digital receivers, the combination of DSP and coherent detection has the prospect to become the technology of choice for the next generation of optical access networks. It will, however, still be important to reduce the cost of the optical network unit (ONU) placed at the customer premises, and to concentrate complex signal processing at the central office where complexity and cost can be shared among a large number of users. The availability of suitable low complexity light sources in particular remains a challenge for such a coherent detection passive optical access network.

In this paper we propose the use of vertical-cavity surface-emitting lasers (VCSELs) as light sources and local oscillator for coherent detection in multi-Gbit/s access systems, due to their cost effective production and capability for chip integration with low threshold and driving current operation. We experimentally demonstrate that by employing a DSP supported coherent receiver to compensate for the transmitter and local oscillator frequency offset and fiber chromatic dispersion, an all-VCSEL, 5 Gbit/s amplitude shift-keying link can be achieved with transmission over 40 km of standard single mode fiber (SSMF) with no optical dispersion compensation with free running and un-cooled VCSEL operation.

2. All-VCSEL digital coherent receiver

Recently, the use of a VCSEL as local oscillator laser source for a coherent receiver has been demonstrated to be feasible [8]. In this case, however the transmitter light source used was a wavelength stabilized distributed feed-back (DFB) laser. The transmitter used a complex in-phase and quadrature (I&Q) optical modulator with external driver amplifiers, and required and extra auxiliary optical signal in an orthogonal polarization state to act as a phase reference at the coherent receiver side. It showed the potential of a VCSEL as a local oscillator although the complete system is rather complex. For applications in FTTC networks, a less complex configuration based on a single technology platform is desirable to reduce cost and overall system integration. Moreover, due to issues of power consumption, an approach based on direct laser modulation will be desirable for next generation access networks.

In this paper, we experimentally demonstrate the use of digital coherent detection using a directly modulated VCSEL as light source for the transmitter and another VCSEL for local oscillator. Traditionally, the broad linewidth of VCSELs has made them unsuitable for coherent detection [9]. By employing digital signal processing algorithms, however, we demonstrate that these limitations can be overcome. Additionally, coherent detection combined with digital signal processing facilitates the use of DSP based chromatic dispersion compensation, thereby eliminating the need for dispersion compensating fiber (DCF) [10]. In combination with the increased sensitivity of coherent detection systems, this makes coherent detection VCSEL based systems a strong candidate for future access networks, while also enabling graceful upgrade due to the ability to operate over the current PON architectures.

Our experimental results show receiver sensitivity up to -36 dBm after 40 km of fiber transmission with no optical amplification or optical dispersion compensation for a 5 Gbps amplitude shift keying (ASK) system. The same system was tested with direct detection, and

employing optical dispersion compensation in the form of 6 km of DCF to compensate 40 km SSMF. The measured sensitivity was -23 dBm and -19 dBm, with and without optical dispersion compensation, respectively. This represents an increase in receiver sensitivity of 13 dB for the coherent system when compared with direct detection system with optical dispersion compensation, and 17 dB compared with direct detection without optical dispersion compensation.

3. Experimental setup

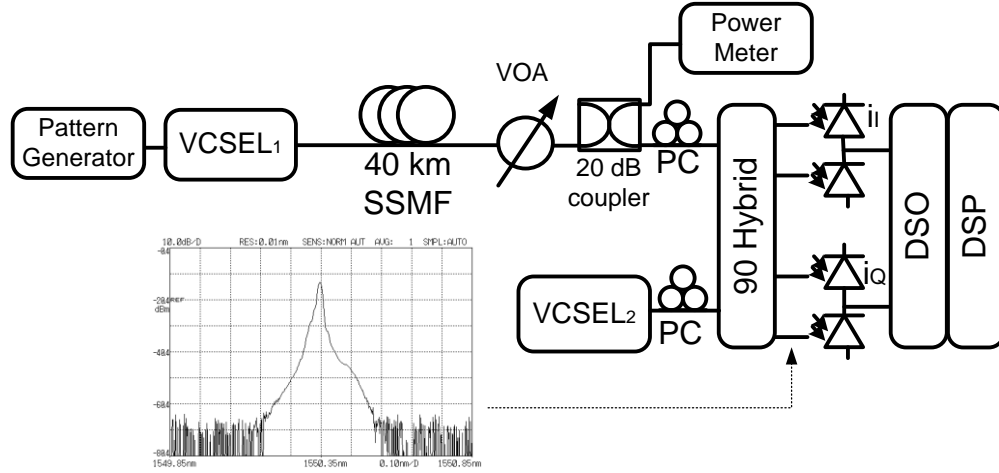


Fig. 1. Experimental setup. Digital sampling scope (DSO), digital signal processing (DSP), polarization controller (PC), variable optical attenuator (VOA). The insertion shows the measured combined optical power spectrum of the signal and the LO.

Figure 1 shows a simplified scheme of our experimental setup. A pulse pattern generator directly modulates a 1550 nm VCSEL (VCSEL₁) at 5 Gbps. A balanced drive configuration is used for the VCSEL₁ with a driving peak-peak voltage of 1 V. The bias current of VCSEL₁ is set to 13.6 mA for optimum performance maximizing the extinction ratio while minimizing overshoot.

Figure 2 shows the optical spectrum of the transmitter VCSEL measured by heterodyne detection with a 100 kHz linewidth external cavity laser (ECL). The frequency offset between VCSEL₁ and the ECL is 5.8 GHz. The measured 3 dB linewidth of VCSEL₁ is 350 MHz.

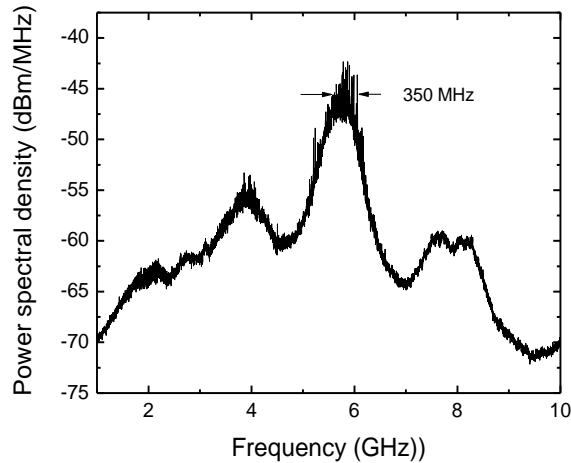


Fig. 2. Laser linewidth of the VCSEL measured by heterodyne detection with an ECL.

The data pattern used for the full VCSEL coherent detection transmission experiment is a pseudo random binary sequence (PRBS) of length of $2^{15}-1$. The average output power of the VCSEL₁ launched into the fiber is 0.6 dBm. The transmission experiment is over 40 km of SSMF with a total attenuation of 7.7 dB, and a total dispersion of 640 ps/nm. In order to measure the optical power going into the coherent receiver, a variable optical attenuator (VOA), a 20 dB coupler and an optical power meter is placed after the transmission fiber. The coherent receiver consists of a 90° optical hybrid and two pairs of balanced photodiodes. The local oscillator (LO) signal is generated by a free running, continuous wave, 1550 nm VCSEL (VCSEL₂). The LO VCSEL₂ has been wavelength tuned to match the wavelength of the transmitting VCSEL₁ at 1550.34 nm by adjusting the bias level to 16.7 mA for intradyne detection. The insertion in Fig. 1 shows the measured optical power spectrum of the signal and the LO. Due to the intradyne detection scheme, the spectrum of the LO is masked by the signal spectrum.

The wavelength tuning range of VCSEL₂ was measured to be 5 nm from 1547 nm to 1552 nm by varying the bias current from 5 mA to 19 mA. This demonstrates the feasibility of bias current wavelength tuning of VCSELs employed as local oscillators in coherent networks. The optical output power of the LO varies from 0.3 mW at 1547 nm to 1.3 mW at 1552 nm.

The in-phase and quadrature components from the coherent receiver are stored with a digital sampling oscilloscope (DSO) with a sampling rate of 40 Gsamples/s. Digital signal processing, consisting of a digital dispersion compensation, synchronization, envelope detection and decision gating, is performed off-line. The detected signals have a random frequency offset. This frequency offset does not affect the demodulation, as the DSP performs envelope detection of the absolute value of in-phase and quadrature components.

4. Results

Figure 3 (a) shows the optical eye diagram at the output of the transmitter. At the bias current of 13.6 mA, beginning overshooting of the VCSEL is observed. The extinction ratio at the transmitter is 6.8 dB measured with an oscilloscope. Figure 3(b) shows the eye diagram after 40 km SSMF transmission. The fiber attenuation has decreased the signal to noise ratio (SNR), and the fiber dispersion has severely distorted the waveform, resulting in significant reduction of eye opening in amplitude as well as time domain.

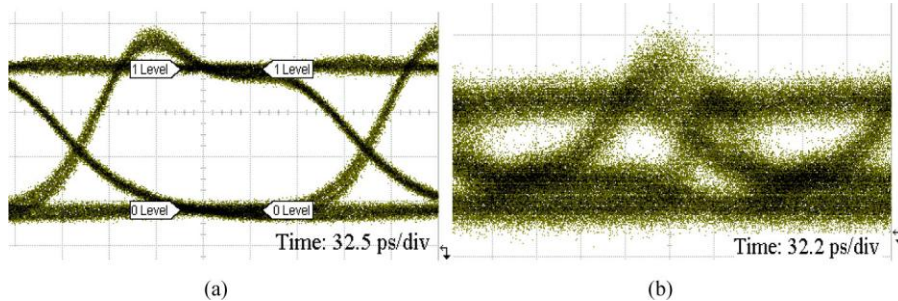


Fig. 3. Optical eye diagrams. 5 Gbps, $I_{\text{bias}} = 13.6$ mA, $V_{\text{pp}} = 1$ V. (a) Back-to-back. (b) After 40 km SSMF

The bit error ratio (BER) of the 5 Gbps signal back-to-back (B2B) and after 40 km SSMF transmission is plotted in Fig. 4. The plot shows the measured BER with direct detection with and without optical dispersion compensation. The plot also shows the BER after coherent detection where the dispersion compensation was performed using DSP.

For direct detection, back to back (B2B) receiver sensitivity at the forward error correction limit of $\text{BER} < 10^{-3}$, was measured to be -23 . After 40 km of SSMF transmission, the measured sensitivity was -19 dBm, corresponding to 4 dB receiver sensitivity penalty. After

DCF for optical dispersion compensation, the measured sensitivity was -23 dBm, and no observable penalty is measured compare to the B2B configuration.

For the coherent detection with DSP based dispersion compensation $2 \cdot 10^5$ bits were stored. DSP dispersion compensation was used to compensate for the chromatic dispersion of the 40 km of SMF transmission link. Best performance after demodulation was achieved by overcompensation so that the total compensated dispersion was 765 ps/nm. This is attributed to the chirp caused by the direct modulation of the VCSEL at the transmitter. Receiver sensitivity was measured to be -36 dBm B2B as well as after transmission, showing that the DSP effectively compensates dispersion. Comparing to the direct detection cases with and without optical dispersion compensation, sensitivity has been improved by 13 dB and 17 dB, respectively.

In order to estimate the number of users that can be reached with this system, a simple power budget calculation has been performed. Considering the launch power of 0.6 dBm, for direct detection without optical dispersion compensation, the total power budget is 19.6 dB with a power margin of 11.9 dB when the 7.7 dB fiber attenuation is taken into account. This corresponds to a passive splitting ratio of 15. By using optical dispersion compensation on direct detection, the total power budget increases to 23.6 dB, but not the power margin which is reduced to 11.5 dB due to the added attenuation of 4.4 dB by the DCF. Therefore, the corresponding passive splitting ratio is reduced to 14 users. For coherent detection the total power budget is 36.6 dB with a margin of 28.9 dB after fiber attenuation. This corresponds to a passive splitting ratio of 776. For the calculation, a total length of 40 km is assumed for the combined metro-access link before the passive splitting point and the distribution fiber link after the passive splitter.

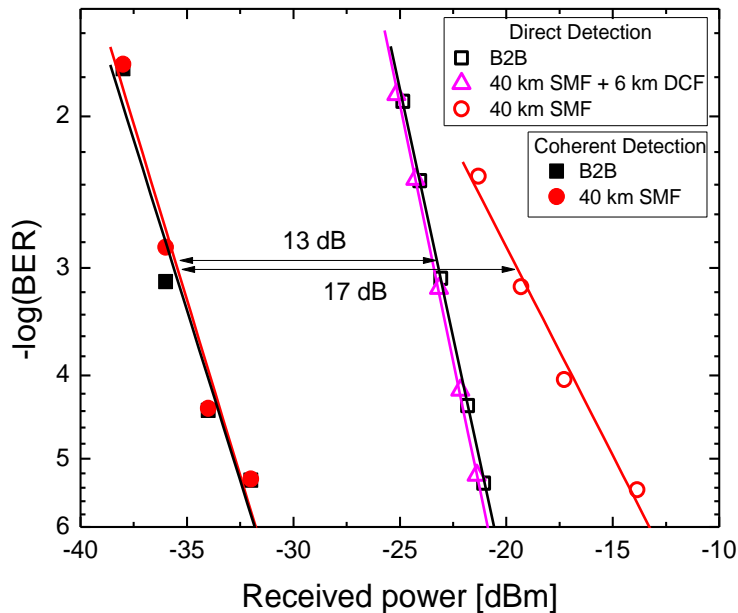


Fig. 4. BER curves after 40 km SMF and for B2B configuration. Bit-rate: 5 Gbps, ER: 6.82 dB, LO power: 0 dBm.

5. Conclusions

We present experimental results, for the first time, demonstrating the feasibility of using VCSELs with uncooled and free running operation as transmitter as well as local oscillator laser in a digital coherent receiver.

The transmitter VCSEL was directly modulated at 5 Gbps, and after 40 km SSMF the signal was received using a coherent receiver with a VCSEL as local oscillator. Sensitivity of -36 dBm has been achieved with 28.9 dB power margin and no need for optical dispersion compensation or optical amplification.

A comparison between coherent detection and direct detection approach has been presented. Coherent detection resulted in a sensitivity improvement of 13 dB and 17 dB, comparing with direct detection with and without optical dispersion compensation, respectively. Moreover, in terms of power budget, power margin for direct detection correspond to a passive splitting ratio of 15, while for coherent detection the achievable splitting ratio is 776.

We have presented what is to the best of the authors knowledge, the first full VCSEL coherent PON link demonstration. The results show the potential for coherent systems to be implemented with low cost optical sources, thereby overcoming one of the main drawbacks of coherent systems for access networks. Therefore, VCSEL-based coherent PONs can be considered as strong candidate for future PONs.

Acknowledgments

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7) under project 212 352 ALPHA "Architectures for flexible Photonic Home and Access networks"; and project 224409 GigaWaM "Gigabit access passive optical network using wavelength division multiplexing".